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Optimization of Deep Drilling Process Parameters of AISI 321 Steel using Taguchi Method

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Abstract

This paper focused on optimizing deep drilling parameters based on Taguchi method for minimizing surface roughness. The experiments were conducted on CNC lathe machine using solid carbide cutting tool on material AISI 321 austenitic stainless steel. Four cutting parameters such as cutting fluid, speed, feed and hole-depth, each at three levels except the cutting fluid at two levels were considered. Taguchi L_{18} orthogonal array was used as design of experiment. The signal-to-noise (S/N) ratio and the analysis of variance (ANOVA) was carried out to determine which machining parameter significantly affects the surface roughness and also the percentage contribution of individual parameters. Confirmation test was conducted to ensure validity of the test result. The results revealed that the combination of factors and their levels $A_2B_3C_2D_1$ i.e. the machining done in the presence of cutting fluid, at a speed of 500 r.p.m. with a feed of 0.04 mm/s and hole-depth of 25 mm yielded the optimum i.e. minimum surface roughness. Further, the results of ANOVA indicated that all four cutting parameters significantly affected the surface roughness with maximum contribution from speed (27.02%), followed by cutting fluid (25.10%), feed (22.99%), and hole-depth (14.29%). It is also observed that the surface finish for deep drilling process can be improved effectively through this approach.

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1. Introduction

Drilling is one of the most commonly used machining processes to produce holes in many industrial components. The surface quality of hole-depth is the main problem associated with deep drilling of machined components. Gillespie (1973) observed that the cost of deburring and edge finishing on precision component may contribute as much as 30% to the cost of parts. Surface roughness is a combination of finer irregularities over machined surfaces due to inherent action of the production process. Shahrom et al. (2013) reported that surface roughness has received great influence on functioning of machined parts which significantly improves creep life, fatigue strength and corrosion resistance.

Literature reveals that twist drills have been the subject of numerous investigations because of their importance in nearly all production operations. AISI 321 austenitic stainless steel bars are extensively used as engineering material in various industries such as Chemical, Aviation and Power plant industries due to less prone to sensitization at elevated temperature (Davis, 2000). AISI 321 austenitic stainless steel bears excellent mechanical properties such as high creep rupture strength, fatigue strength and high corrosion resistance including low weight to strength ratio. Peckner and Bernstein (1977) reported that AISI 321 austenitic stainless steel is widely used in super heater tubing, coal fired boilers, tubes, pipes and pressure vessels of gas cooled nuclear reactors due to excellent mechanical properties. Islam et al. (2009) found that several factors influence the quality of drilled holes such as cutting parameters and cutting tool configurations. Kivak et al. (2012) employed Taguchi method to optimize drilling parameters for surface roughness and thrust force in dry cutting conditions of AISI 316. Cicek et al. (2013) studied the effects of cryogenic treatment and drilling parameters of AISI 304 stainless steel under dry conditions. They investigated that feed rates and cutting speed are most significant factors with percentage contribution of 83.07% and 64.365% respectively on surface roughness and roundness error. Ilhan and Harun (2011) performed dry turning on hardened AISI 4140 and optimized turning parameters to minimize surface roughness.

The survey of literature indicates that there are published works on the effect of process parameters on surface roughness. However, very limited literature is available on the study of the effect of drilling process parameters on AISI 321 austenitic stainless steel bars. Due to wide range of applications of AISI 321 austenitic stainless steel, an attempt has been made in this study to optimize deep drilling parameters such as cutting fluid, speed, feed and hole-depth for minimum value of surface roughness. This is accomplished by using Taguchi method (Abuelnaga and El-Dardiry, 1984; Chrysosolouris and Guillot, 1990; Chua et al., 1993). In this paper, the Taguchi method is introduced first. The experimental details of using the Taguchi method to determine and analyze the optimal cutting parameters are described next. Finally, the paper concludes with a summary of this study and future work.

2. Taguchi Method

Taguchi method is one of the simplest and effective approaches for parameter design and experimental planning (Fisher, 1925). In this method, the term ‘signal’ represents the desirable value (mean) for the output characteristic and the term ‘noise’ represents the undesirable value i.e. standard deviation (S.D.) for the output characteristic. Therefore, the S/N ratio is the ratio of the mean to the S.D. There are three types of S/N ratio depending on type of characteristics-the lower-the-better, the higher-the-better, and the nominal-the-better. The details of the calculation of the S/N ratio for these three types of characteristics are available in Siddiquee et al. (2010). Optimization of quality characteristics using parameter design of the Taguchi method are summarized in the following steps (Nian et al., 1990):

- Identification and evaluation of quality characteristics and process parameters.
- Identification of number of levels for the process parameters and possible interactions between the process parameters.
- Assignment of process parameters to the selected appropriate orthogonal array.
- Conduction of experiments based on the arrangement of the orthogonal array.
- Calculation of S/N ratio.
- Analyze the experimental results using the S/N ratio and ANOVA.
- Selection of the optimal levels of process parameters.
- Verification of the optimal process parameters through the confirmation experiment.

3. Drilling Process Experiments

Drilling is a versatile machining process used to produce holes with the use of multi-edged cutting edges by removing material from the surface of a work-piece. Drilling is a complicated process and many factors affect the quality of the machined surface. In this study, deep drilling is performed on AISI 321 austenitic stainless steel bars which are difficult to machine alloy. The deep drilling is conducted on a CNC lathe machine that produces deep hole at a specified rate of rotational speed, feed and hole-depth in either presence or absence of cutting fluid. Cutting fluid is used to lubricate the machined surface and too reduce heat from the tool and the work-piece. Therefore, four cutting parameters, i.e. cutting fluid, speed, feed rate, and hole-depth must be determined in a deep drilling operation. Since purpose of deep drilling operations is to produce minimum surface roughness of machined surface, therefore, surface roughness is an important index to evaluate cutting performance. As surface roughness is strongly correlated with cutting parameters such as cutting fluid, speed, feed rate, and hole-depth (Shaw, 2005), the present study is conducted to select optimum cutting parameters to improve machining performance with improved surface finish.

3.1. Selection of cutting parameters and their levels

The deep drilling tests were performed on a CNC lathe machine (Make: Jyoti, India; Model: DX 150; Tool movement: X-150 mm, Z-350mm, and 5.5-KW/4500 rpm). A photograph of experimental setup is shown in Figure-1.

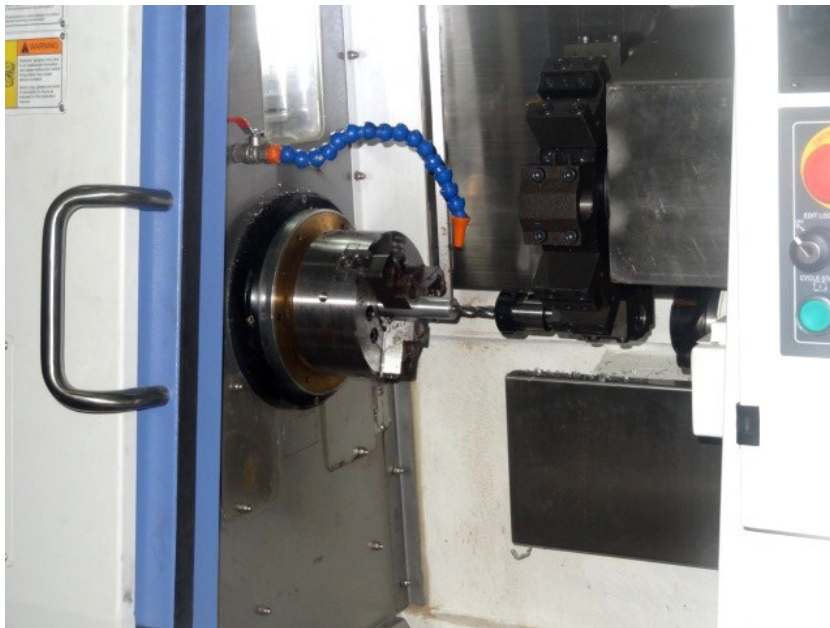


Figure 1. Experimental Setup.

A water soluble mineral oil (Trade name: Hocut 795-H, Origin: Houghton International Inc., USA) was used as cutting fluid. Deep drilling operation was performed using K- series Solid carbide drill. The diameter of drill was selected as 10 mm. AISI steel bars round bars of 25 mm diameter with length 60 mm were used as work piece material. Chemical compositions of AISI 321 austenitic stainless steel bars used in the experiments are shown in Table 1.

Table 1. Material composition.

Element	Concentration (% by weight)	Element	Concentration (% by weight)
Iron	70.41	Molybdenum	0.53
Carbon	0.078	Aluminum	0.055
Silicon	0.419	Copper	0.491
Manganese	1.43	Chromium	18.30
Sulphur	0.041	Niobium	0.045
Phosphorous	0.034	Vanadium	0.001
Nickel	8.14	Zirconium	0.006

The initial cutting parameters were as follows: speed 300 r.p.m.; feed rate 0.03 mm/s; hole-depth 25 mm with presence of cutting fluid. The feasible range for the cutting parameters was defined by varying the speed in the range 300-500 r.p.m.; feed rate in the range 0.03-0.05 mm/s; hole-depth in the range 25-35 mm. Therefore, three levels of the cutting parameters along with two level of one cutting parameter i.e. cutting fluid 'absent' and 'present' were selected shown in Table. 2.

Table 2. Cutting parameters and their levels.

Factor identifier	Factor	Level 1	Level 2	Level 3
A	Cutting fluid	Absent	Present	
B	Speed (r.p.m.)	300	400	500
C	Feed (mm/s.)	0.03	0.04	0.05
D	Hole-depth (mm)	25	30	35

3.2 Machining performance measure

Out of various surface finish parameters i.e. roughness average (R_a), root-mean-square (rms) roughness (R_q), and maximum peak-to-valley roughness (R_y or R_{max}) the parameter R_a (Webmaster PDI, 2004; Yang and Chen, 2001), which is most widely used in industry, was selected in this study. Eighteen experiments based on orthogonal array L_{18} were conducted for different settings of cutting fluid, speed, feed and hole-depth (Table 2). The surface roughness of all the specimens was measured using the Taylor-Hobson SurfCom instrument for a sampling length of 5 mm, as per the recommendations of ASME B-46.1-2002. The measured R_a values are shown in Table 4.

4. Determination of Optimal Cutting Parameters

In this section, the use of an orthogonal array to reduce the number of cutting experiments for determination of optimal cutting parameters is presented. Results of the cutting experiments are studied by using the S/N ratio and ANOVA. Based on the results of these analyses, optimal cutting parameters for minimum surface roughness are obtained and verified.

4.1. Orthogonal array experiment

In order to select an appropriate orthogonal array for experiments, the total degrees of freedom need to be computed. The degrees of freedom are defined as the number of comparisons between process parameters that need to be made to determine which level is better and specifically how much better it is. For example, a three-level process parameter counts for two degrees of freedom. The degrees of freedom associated with interaction between two process parameters are given by the product of the degrees of freedom for the two process parameters. In this

study, the interaction between the cutting parameters is neglected. Therefore, there are six degrees of freedom for three process parameters (speed, feed and hole-depth) and one degree of freedom for cutting fluid. Once the degrees of freedom are evaluated, the appropriate orthogonal array is selected to serve the specific purpose. Basically, the degrees of freedom for the orthogonal array should be greater than or at least equal to those for the process parameters. In this study, an L_{18} orthogonal array was used for eighteen experiments as shown in Table 3.

Table 3. Experimental layout using an L_{18} orthogonal array.

Experiment No.	Cutting parameter level			
	A Cutting fluid	B Speed	C Feed	D Hole-depth
1	1	1	1	1
2	1	1	2	2
3	1	1	3	3
4	1	2	1	1
5	1	2	2	2
6	1	2	3	3
7	1	3	1	2
8	1	3	2	3
9	1	3	3	1
10	2	1	1	3
11	2	1	2	1
12	2	1	3	2
13	2	2	1	2
14	2	2	2	3
15	2	2	3	1
16	2	3	1	3
17	2	3	2	1
18	2	3	3	2

4.2. Analysis of the signal-to-noise (S/N) ratio

As defined earlier, there are three categories of performance characteristics, i.e., the lower-the-better, nominal-the-better and the higher-the-better. In this study, the lower-the-better performance characteristic is chosen to obtain minimum surface roughness. The experimental results for surface roughness and the corresponding S/N ratios are shown in Table 4. Since the experimental design is orthogonal, it is then possible to separate out the effect of each cutting parameter at different levels. For example, the mean S/N ratio for the speed at levels 1, 2 and 3 can be calculated by averaging the S/N ratios for the experiments (1-3 & 10-12), (4-6 & 13-15) and (7-9 & 16-18) respectively. The mean S/N ratio for each level of the other cutting parameters can be computed in the similar manner. The mean S/N ratio for each level of the cutting parameters is summarized and called the mean S/N response table for surface roughness (Table -5). In addition, the total mean S/N ratio for the eighteen experiments is also calculated and given below Table 5.

The mean S/N ratio graph for surface roughness is shown in Figure 2. The S/N ratio corresponds to the smaller variance of the output characteristics around the desired value.

Table 4. L_{18} Machining Orthogonal array with the values of response variables.

Expt. No.	A	B	C	D	Surface Roughness R_a μm	Calculated S/N ratio for surface roughness
1	1	1	1	1	4.10	-12.26
2	1	1	2	2	3.74	-11.08
3	1	1	3	3	4.25	-10.18
4	1	2	1	1	4.43	-11.98
5	1	2	2	2	4.34	-11.91
6	1	2	3	3	4.21	-10.58
7	1	3	1	2	3.98	-10.68
8	1	3	2	3	3.94	-10.58
9	1	3	3	1	3.21	-10.26
10	2	1	1	3	4.14	-10.58
11	2	1	2	1	3.24	-11.95
12	2	1	3	2	3.42	-10.21
13	2	2	1	2	4.17	-12.26
14	2	2	2	3	3.64	-12.75
15	2	2	3	1	3.67	-12.28
16	2	3	1	3	3.71	-11.93
17	2	3	2	1	3.14	-12.00
18	2	3	3	2	3.38	-10.93

Table 5. Mean S/N response table for surface roughness.

Cutting parameters	Mean S/N ratio			
	Level 1	Level 2	Level 3	Max – Min
A	-12.05	-11.12		0.94
B	-11.59	-12.18	-10.99	1.19
C	-12.22	-11.25	-11.29	0.97
D	-11.13	-11.64	-11.99	0.86

The total mean S/N ratio = -11.59

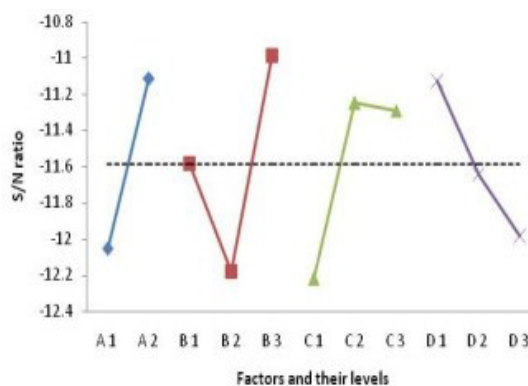


Figure 2. Mean signal-to-noise ratio graph.

4.3. Analysis of variance (ANOVA)

The purpose of ANOVA was to investigate which deep drilling parameters significantly affected the performance characteristics. This was accomplished by separating the total variability of the S/N ratios, which is measured by the sum of the squared deviations from the total mean of the S/N ratio, into contributions by each of the process parameters and the error. First, the total sum of the squared deviations SS_T from the total mean of the S/N ratio η_m (Khan et al., 2006) is calculated using Equation 1.

$$SS_T = \sum_{i=1}^n (\eta_i - \eta_m)^2 \quad (1)$$

Where n is number of experiments in the orthogonal array, η_i is the mean S/N ratio for the i -th experiment.

The total sum of squared deviations SS_T is decomposed into two sources: the sum of squared deviations SS_d due to each process parameter and the sum of squared error SS_e . The percentage contribution p by each of the process parameter in the total sum of squared deviations SS_T is a ratio of the sum of squared deviations SS_d due to each process parameter to the total sum of squared deviations SS_T .

Statistically, there is a tool called the F – test to see which process parameters have significant effect on the quality characteristic. For performing the F – test, the mean of squared deviations SS_m due to each process parameter needs to be calculated. The mean of squared deviations SS_m is equal to the sum of squared deviations SS_d divided by the number of degrees of freedom associated with the process parameter. Then, the F value for each process parameter is simply the ratio of the mean of squared deviations SS_m to the mean of squared error SS_e . Usually, when $F > 4$, it means that the change of the process parameter has significant effect on the quality characteristics.

Table 6 shows the results of ANOVA for the surface roughness. It is found that the change of cutting parameters in the range given in Table 1 has significant effect on the surface roughness since F value for all cutting parameters is more than 4. Therefore based on Table 6 and Fig. 2 the optimal cutting parameters are $A_2B_3C_2D_1$ for factors A, B, C and D, respectively.

The results of ANOVA also reveals that the speed is the most significant deep drilling process parameters for affecting the surface roughness characteristics due to its highest percentage contribution speed (27.02%) amongst the selected process parameters. Table 6 further shows that the percentage contribution of other parameters in decreasing order is cutting fluid (25.10%), feed (22.99%) and hole-depth (14.29%).

Table 6: Results of the analysis of variance.

Symbol	Machining parameters	Dof	Sum of square	Mean square	F -value	Contribution %
A	Cutting fluid	1	3.95	3.95	23.69	25.10
B	Speed	2	4.25	2.12	12.75	27.02
C	Feed	2	3.61	1.81	10.85	22.99
D	Hole-depth	2	2.25	1.12	6.74	14.29
Error		10	1.67	0.17		10.60
Total		17	15.72			100.00

4.4 Confirmation test

After obtaining the optimal level of the deep drilling process parameters, the next step is to verify the percentage change of surface roughness between predicted and experimental value for this optimal combination. Table 7 compares the results of the confirmation experiments using the optimal deep drilling process parameters ($A_2B_3C_2D_1$) obtained by the proposed method and with those of the initial deep drilling process parameters ($A_2B_3C_2D_1$).

Table 7. Results of Confirmation Test.

Level	Initial cutting Parameters $A_1B_1C_1D_1$	Optimal machining parameters	
		Prediction $A_2B_3C_2D_1$	Experiment $A_2B_3C_2D_1$
Surface roughness (μm)	4.10	5.40	3.14
S/N ratio (db)	-12.26	-14.65	-9.94
Improvement in S/N ratio = 2.32			

As shown in Table 7, that S/N ratio improved from -14.65 to -9.94 (an improvement of 32.15%) due to decrease of surface roughness from 5.40 to 3.14 μm (a decrement of 71.97%) which shows that optimal combination ($A_1B_1C_3D_3$) of the deep drilling process parameters are good enough to reduce the roughness of the machined surface.

5. Conclusion

This paper has focused an application of the Taguchi method for the optimization of process parameters of deep drilling operations. As discussed earlier, the parameter design of the Taguchi method provides a simple, systematic, and efficient methodology for the optimization of the cutting parameters. Except hole-depth, cutting parameters such as speed, feed, and cutting fluid mainly influenced the surface roughness in deep drilling of AISI 321 austenitic steel bars. The optimal combination of deep drilling parameters and their levels for the minimum surface roughness of the deep drilling process are $A_2B_3C_2D_1$ (i.e. Cutting fluid-present, speed-500 r.p.m., feed rate-0.04mm/s and hole-depth-25mm). The confirmation experiments were conducted to verify the optimal cutting parameters. The percentage contributions of speed, cutting fluid, feed and hole-depth are 27.02%, 25.10%, 22.99% and hole-depth 14.29% respectively. The improvement of surface roughness from initial cutting parameter to the optimal cutting parameters is about 131%. Hence, significant improvements in surface roughness can be obtained using this approach. Finally, it can be a very useful technique for use to the industries to optimize the machining performance with minimum cost and loss of time.

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